Reports

A Model of Solar Luminosity Modulation by Magnetic Activity Between 1954 and 1984

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A simple model based on the changes in excess radiation from bright magnetic faculae and on changes in reduced radiation from dark spots is remarkably successful in matching the slow variations of total solar irradiance measured simultaneously by the ERB and ACRIM satellite radiometers between 1981 and 1984. This model was extended back to 1954 to reconstruct the modulation of irradiance by magnetic activity during the past three 11-year solar cycles. The model predicts that the sun is consistently brighter at activity maximum than at minimum. The 0.07 percent brightening at the peak of the last cycle in 1980 was more pronounced than the brightenings found for either of the two previous cycles, even though cycle 19, which peaked around 1957, had the largest sunspot number amplitude in the history of reliable sunspot records.

The variability of the total solar radiative output over the 11-year activity cycle has been the focus of considerable study since the earliest repeatable solar constant measurements some 75 years ago (*1*). The possibility that solar irradiance variations significantly influence climate (*2*) provides an important motivation for these studies, leading to the present series of highly precise radiometer measurements from the Nimbus-7 and Solar Maximum Mission (SMM) satellites (*3*).

A recent study (*4*) has shown that in addition to previously recognized day-to-day variations (*5*), the signals measured by these two radiometers rise and fall in unison on time scales of 4 to 9 months with a variation amplitude of 0.04 to 0.07%. This common variation and also the monotonic downtrend seen in both radiometers were found to result, at least since 1981, mainly from changes in the continuum emission of the bright photospheric magnetic regions known as faculae (*6*). The dominant role played by the bright faculae seems to have caused the sun to brighten at peak activity levels of the last activity cycle during 1980–1981, rather than dimming as might be expected if dark spots alone influenced the photospheric heat flow.

The simple model put forward in that study, which successfully reproduces the variations observed independently by the ERB and ACRIM radiometers, includes the reduction of total irradiance, S, produced by the dark spots as well as the brightening caused by the faculae. We first calculate a function, P_s, that estimates the fractional reduction of S caused by dark spots from the observed daily projected areas and disk coordinates of sunspots using a published value of a broad-band photometric sunspot contrast averaged over the umbra and penumbra.

The photometric contrast of the faculae in the photospheric visible and near-infrared continuum is low except very near the solar limb (*6*), and the total area covered by the many small facular regions is also too uncertain to enable us to reliably calculate a photometric function, analogous to P_s, that would directly estimate the contribution of the bright elements to irradiance variation. For this reason, to evaluate the facular influence on S, we proceed by subtracting the P_s time series from the time series of daily irradiance measurements made by either the ERB or ACRIM radiometer. The resulting irradiance residuals, $S - P_s$, exhibit substantial variations that correlate very well with variations in indices of the radiation from bright facular elements during 1981–1984 (*4*).

Facular indices are based on daily observations of the solar disk in optical line or microwave continuum radiations. These are emitted by the generally hotter chromospheric and coronal plasmas that overlie the photospheric layers of the facular atmosphere where almost all of its integrated radiation originates. The line and microwave emissions are much more enhanced relative to the undisturbed atmosphere than are the facular white light emissions that carry most of the radiative output from these bright magnetic elements. Consequently, the variation of these indices provides a convenient estimate of day-to-day changes in the total area and integrated broad-band brightness of faculae on the disk.

Some facular areas can be discerned near the limb in a white light photograph of the sun's disk such as Fig. 1, top. The relatively high contrast of the faculae in the narrow band radiation of a strong chromospheric resonance line is illustrated in Fig. 1, bottom. We see from Fig. 1 that the largest faculae occur in active regions, generally accompanied by spots. However, a network of smaller facular elements is also seen in Fig. 1, bottom, to cover the whole solar surface. The faculae referred to here include both those in the active regions and in the network.

We then use the regression curve found to hold in 1981–1984 between the solar irradiance residuals $S - P_s$ and such a facular index, to reconstruct the residuals over some longer period for which values of the facular

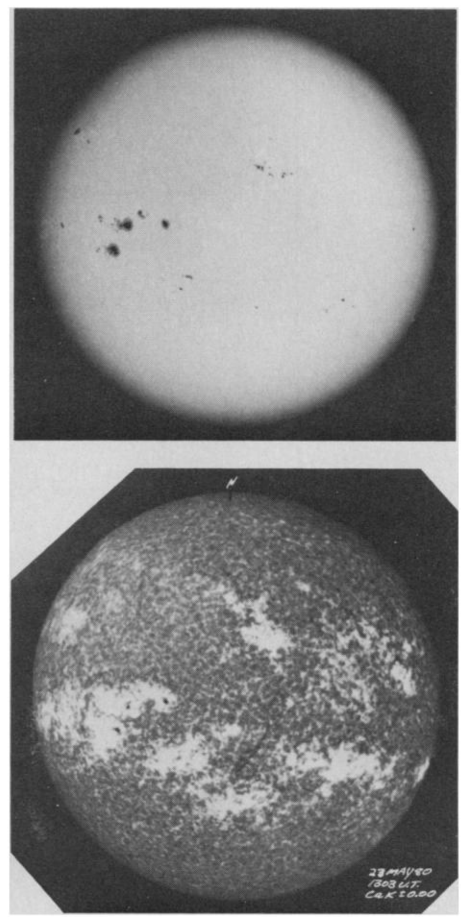

Fig. 1. Faculae and spots seen nearly simultaneously on 23 May 1980 (**top**) in integrated white light and (**bottom**) in the narrow band absorption of the CaII K resonance line. In white light the faculae are visible only near the limb, where their photometric contrast increases to about 10%. In the CaII absorption line they are seen with good contrast across the whole disk. [Photograph courtesy of the National Solar Observatories, Association of Universities for Research in Astronomy, Inc.]

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index are available. Finally, to obtain our model of the total irradiance variation we add to the time series of the reconstructed residuals the time series of P_s, available from 1874 to the present.

Computation of the past behavior of S with this model is limited by the available database of suitable indices of bright faculae. The only full disk index available for estimating facular variations prior to cycle 21 is provided by the daily 10.7-cm microwave flux ($F_{10.7}$) data obtained by the Herzberg Institute for Astrophysics in Ottawa since 1954. The regressions of monthly mean $S - P_s$ upon the $F_{10.7}$ index are shown in Fig. 2, for the ERB and ACRIM data during 1981–1984. The relation is linear, as expected, since the microwave emissions of the relatively dense and hot plasmas overlying the photospheric faculae are known to be strongly enhanced (*7*).

In Fig. 3 we show the residuals $S - P_s$ reconstructed with the regression data, compared in each case with the observed residuals obtained with the two radiometers during 1981–1984. During this period when the ERB and ACRIM radiometers were observed to track one another best, the regressions are least likely to be contaminated by low-level radiometer calibration drifts (*4*) and the residuals reconstructed with the $F_{10.7}$-cm regression track the observed residuals quite well. They reproduce not only the main rises and falls common to the ACRIM and ERB residuals, but also their general downtrend between 1981 and 1984.

A linear relation is found (*4*) between the 4- to 9-month variation in the irradiance residuals, and facular indices more closely related to photospheric levels than is the 10.7-cm flux. This indicates that such variations can be attributed to the evolution of large complexes of solar magnetic activity (*8*). A good match is found between the overall downtrend in total irradiance and that predicted from full disk indices that include the network faculae as well as those in active regions (*4*). Since the slow trend is not reproduced when an index of only active region faculae is used, we conclude in (*4*) that this downtrend is caused by the slow decrease in radiation from the network faculae. This is consistent with the general decay of photospheric magnetic fields between activity maximum and minimum in the last solar cycle (*9*).

The behavior of the total irradiance over the last three solar cycles as computed with this model is shown in Figs. 4 and 5. Figure 4A shows the negative sunspot irradiance contribution, P_s, calculated for 1954–1984. It exhibits minima at peak sunspot activity levels around 1958, 1970, and 1981. Figure 4B shows the (positive) facular contribution, P_f, calculated from the regression of ACRIM irradiance residuals against the $F_{10.7}$ flux shown in Fig. 2. This function exhibits maxima at peak activity levels. Figure 4C shows the reconstructed solar irradiance for 1954–1984, obtained by adding the P_s and P_f functions. In Fig. 5 we compare the reconstructed irradiances calculated from the two regressions based on ACRIM and ERB data shown in Fig. 2, which are seen to yield similar results.

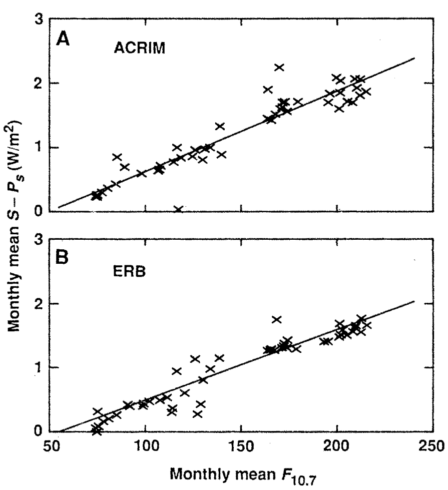

Fig. 2. Regressions of the irradiance residuals $S - P_s$ formed with data from (**A**) ACRIM and (**B**) ERB, upon the 10.7-cm microwave flux during 1981–1984. Monthly binned data have been used.

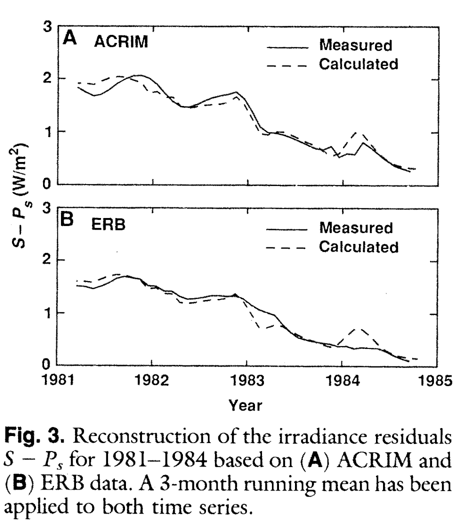

Fig. 3. Reconstruction of the irradiance residuals $S - P_s$ for 1981–1984 based on (**A**) ACRIM and (**B**) ERB data. A 3-month running mean has been applied to both time series.

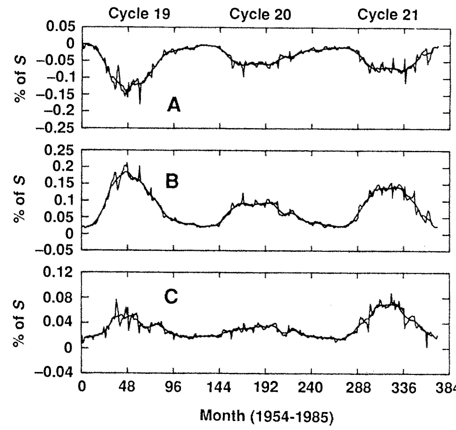

Fig. 4. Plots of (**A**) the sunspot contribution to total irradiance, (**B**) the facular contribution obtained from the $F_{10.7}$ regression against the ACRIM data, and (**C**) their cumulative effect, all shown as a percentage of the total irradiance for the period of 1954–1984.

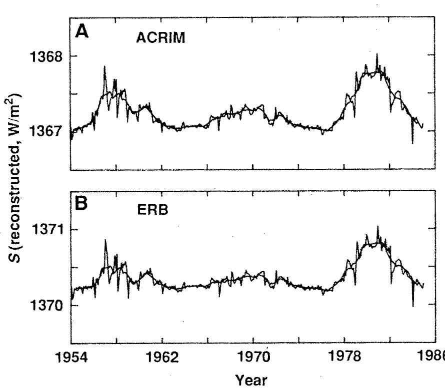

Fig. 5. Behavior of the total solar irradiance between 1954 and 1985 reconstructed with (**A**) the ACRIM data and (**B**) ERB data. The heavy line represents a 12-month running mean. The difference in the absolute scales in the two panels arises from a difference in the ACRIM and ERB absolute calibrations.

We find that the sun is consistently brighter around activity maximum than around minimum. This is contrary to the predictions of an earlier model (*10*) in which the sunspot-induced reduction of photospheric brightness dominated facular enhancements. In our model, the total excess radiation of the low-contrast faculae covering a relatively larger area more than compensates the reduced emission of the much higher contrast dark sunspots that cover a smaller fraction of the photospheric surface. This finding seems to rule out the idea that the influence of bright facular and dark sunspot magnetic elements on photospheric heat flow cancel globally, leaving the solar luminosity unaffected (*11*).

The amplitude of the 11-year total irradiance modulation predicted by this model varies significantly over the last three cycles. Specifically, the 0.07% amplitude of the modulation over the last cycle 21 was significantly larger than during either of the two preceding cycles 19 and 20. The relatively small modulation of S found for cycle 19 is particularly surprising, since the amplitude of this cycle was the highest in the approximately 150-year history of reliable sunspot records (*12*). It appears that the behavior of solar luminosity and total irradiance over the 11-year cycle are determined by the relative levels of facular and sunspot activity, rather than by the excursion in either one of these activity indices considered alone.

The magnitude of the 4- to 9-month variations in total solar irradiance discussed here is consistent with the observed photometric contrast in visible light of spots and large faculae, and with their measured area variation (*13*). The simplest and best studied model of photospheric faculae explains their excess brightness as a direct result of their intense, vertical magnetic fields (*6*). Assuming even approximate magnetohydrostatic equilibrium, these kilogauss fields must reduce the local plasma pressure and thus its opacity. According to this model, this enables radiation to escape from deeper and hotter photospheric layers. The same effect should operate in spots, but in these larger diameter flux tubes, the inhibition of convective heat transport to the surface is expected to more than compensate, thus perhaps explaining their darkness.

The slower trends in total irradiance that we attribute to the decay of the network faculae may be explainable in terms of the same model of faculae as local heat leaks, although estimates of the facular network contrast and slow variations in area are difficult. The photometric contrast of faculae is known to increase roughly as inverse wavelength λ^{-1} (*14*) and is relatively large in the ultraviolet continuum (*15*). Estimates of the total irradiance variation expected from facular radiations of wavelength below 300 nm (*16*) suggest that a significant fraction of the total irradiance variations might arise from changing outputs from these magnetic structures in the 200- to 300-nm spectral region.

It is clearly of interest to test our model with a longer time base of radiometry. The variations studied here have amplitudes that are at the limit of the long-term calibration stability of either the ACRIM or ERB considered alone. It is highly desirable that the operation of both radiometers be maintained at least through the peak of the next solar cycle expected around 1991. Such measurements should finally resolve the classical question of the amplitude and phase of the total solar irradiance variability over the activity cycle, and begin the investigation of possible longer term secular trends in total solar output, such as those suggested by recent photometric analysis of sun-like main sequence stars (*17*).

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Protein Carbon-13 Spin Systems by a Single Two-Dimensional Nuclear Magnetic Resonance Experiment

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By applying a two-dimensional double-quantum carbon-13 nuclear magnetic resonance experiment to a protein uniformly enriched to 26 percent carbon-13, networks of directly bonded carbon atoms were identified by virtue of their one-bond spin-spin couplings and were classified by amino acid type according to their particular single- and double-quantum chemical shift patterns. Spin systems of 75 of the 98 amino acid residues in a protein, oxidized *Anabaena* 7120 ferredoxin (molecular weight 11,000), were identified by this approach, which represents a key step in an improved methodology for assigning protein nuclear magnetic resonance spectra. Missing spin systems corresponded primarily to residues located adjacent to the paramagnetic iron-sulfur cluster.

RAPID PROGRESS HAS BEEN MADE in applying two-dimensional nuclear magnetic resonance (2D NMR) techniques (*1*) to proteins (*2*). Extensive ^{1}H NMR assignments have been obtained for more than 50 small proteins (*3*), and these assignments have enabled the determination of solution structures based on NMR cross-relaxation and coupling information (*2, 4*). Carbon-13 NMR has been neglected in the more popular strategies of protein spectroscopy, largely because of the low sensitivity of the experiment at the natural abundance concentration of ^{13}C (1.1%). Cross-assignments of ^{1}H-^{13}C groups in proteins have been achieved by 2D NMR approaches involving either ^{13}C detection (*5*) or the more efficient ^{1}H detection (*6*). However, extensive sequence-specific assignments are available to date only for the backbone carbon atoms of two small proteins (*7*), and only limited ^{13}C assignments of side chain resonances have been achieved (*8*).

In protein NMR spectroscopy, the conventional first step in obtaining sequence-specific assignments has been the analysis and classification of ^{1}H spin systems. This procedure requires the collection of 2D NMR data by two or more protocols [usually NOESY and COSY, as well as RELAY, HOHAHA, or similar methods (*9*)] followed by lengthy data-processing and spectral analysis. Some ambiguity usually exists in the spectral analysis because of similarities between the ^{1}H spin systems of several amino acid residues. For example, 8 of the 20 amino acids share the AMX spin system

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